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**SPECIAL ISSUE**

# The role of models/and analogies in science education: implications from research

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Models and modelling are key tools for scientists, science teachers and science learners. In this paper we argue that classroom-based research evidence demonstrates that the use of models and analogies within the pedagogy of science education may provide a route for students to gain some understanding of the nature of science. A common theme to emerge from the literature reviewed here is that in order to successfully develop conceptual understandings in science, learners need to be able to reflect on and discuss their understandings of scientific concepts as they are developing them. Pedagogies that involve various types of modelling are most effective when students are able to construct and critique their own and scientists' models. Research also suggests that group work and peer discussion are important ways of enhancing students' cognitive and metacognitive thinking skills. Further we argue that an understanding of science models and the modelling process enables students to develop a metacognitive awareness of knowledge development within the science community, as well as providing the tools to reflect on their own scientific understanding.

## Introduction

Students, whether they realize it or not, encounter science in their everyday lives. This may take the form of current debates reported in the media; for example, the use of genetically modified organisms, the relevance of sustainability within our economy and the ethics of reproductive technologies. It appears that students, like the general public, have limited understanding of the nature of science and how scientists conduct their 'business' (see, for example, Justi and Gilbert in press). As soon as scientists attempt to explain macroscopic nature (e.g. physical and chemical properties of substances, chemical behaviour) they inevitably resort to the use of models (Coll in press). Thus, models and modelling are key features of science and consequently of science education when there is an attempt to make accessible scientists' understandings and to provide some insight into their business. Some authors, for example, consider that to understand science is to understand the models used by scientists (Harrison and Treagust 1996).

In recent years the importance of models in science education has been recognized with an increasing amount of research attention (Franco et al. 1999, Gilbert and Boulter 2000, Greca and Moreira 2000) and there are several significant New Zealand studies to draw on (Coll 1999, France 2000, Taylor 2000). Research evidence indicates that models, metaphors and analogies are already widely used as

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metacognitive tools in science teaching (Duit 1991, Franco et al. 1999, Greca and Moreira 2000, Harrison and Treagust 1996).

This paper will argue that research evidence demonstrates that the use of analogies and models within the pedagogy of science education may provide a route for students to gain some understanding of the nature of science and the scientific enterprise. In addition, recent research has shown that some pedagogical approaches to model use have enabled students to develop a metacognitive awareness as well as providing the tools to reflect on their own scientific understanding.

This paper will:

- define analogies and models in terms of their use in the scientific enterprise and as a teaching tool;
- examine the research literature that identifies learners' difficulties with analogy and model use in science education;
- present and evaluate professional development research on the use of models in science education;
- justify the importance of a model-based pedagogy when applying sociocultural approaches to teaching and learning;
- explore some strategies that enable learners to develop an understanding of model development through group work and collaborative knowledge building in science; and
- summarize the findings and make some observations for further research.



## Definitions and use of models and analogies in science and science education

A model is a representation of an idea, object, event, process or a system (Gilbert and Boulter 2000). Mental models are a special form of model and are defined as human cognitive constructions (Ritchie et al. 1997, Smit and Finegold 1995) used to describe and explain phenomena that cannot be experienced directly. Mental modelling is an activity undertaken by individuals, whether alone or within a group, in an attempt by humans both to understand the world and, when expressed publicly, to articulate their concepts to others (Harrison and Treagust 1996). Mental models are not to be confused with expressed models and the analogies that are often used to represent the mental model (see later). The following is a helpful framework for discussing different kinds of models used in science (Gilbert and Boulter 2000).

- Mental models that are expressed in the public domain through action, speech, writing or other symbolic form are called *expressed models*.
- Expressed models that gain social acceptance following testing by the community of professional scientists become *consensus models*.
- Consensus models that are currently in use at the frontiers of science may be termed *scientific models*, while those produced in specific historical contexts and later superseded may be called *historical models*.

Models play an essential role in the practice of science (Ogborn and Martins 1996). Accounts of the work of professional scientists are dominated by the building and testing of mental models (Penner et al. 1997). Well-known historical examples include Rutherford's solar system mental model of the atom, and Volta and Ampere's representations of electricity in terms of the pressure and flows of liquids

(Stavy 1991). In fact, science does not proceed without recourse to mental models and expressed models because of their necessary and central role both in research and in the communication of knowledge (Dagher 1994, Treagust 1993).

The crucial role of models in science practice provides the justification for the inclusion of models in science teaching. The assumption is that it provides a link between these two worlds, and that acquiring an understanding of the role of models contributes to an 'authentic' science education in which the education reflects the nature of the parent discipline (chemistry, physics, etc.) as much as possible (Gilbert et al. 2000).

In fact, models and modelling already play an important role in teaching and teachers commonly use models to explain ideas to students (Duit 1991). These expressed models are sometimes identified as teaching models (France 2000, Zimmermann 2000). Examples of these expressed teaching models include: two-dimensional models, such as those found in textbook diagrams; three-dimensional models, such as scaled miniatures, scaled enlargements and working models; and visual and verbal metaphors and analogies, either in text or presented by teachers. Each of these models represents a mental model in some, but not all, of its properties. That is, they are simplified representations of phenomena or ideas in that they take up an intermediate position between reality and a mental model.

Analogies may be considered a subset of models as they involve the comparison between two things that are similar in some respects. They are often used by scientists to explain abstract science concepts as well as when they are developing the complexity of their mental models. Ault (1998) notes that exemplary teachers share this strategy of using analogy with scientists when they are expressing complex abstract ideas. To further support this link, Hesse (1966) uses the process of drawing an analogy where two things are compared so that the target (that which is be presented) is viewed in terms of the source (possessing similarities) to provide the framework for model building. From this premise it is important to draw students' attention to the use and value of analogies in model development activities (BouJaoude and Tamim 2000) as well as be conversant with the role of analogies in model development.

## Difficulties encountered with model and analogy use in science education

There is a great deal of literature that documents the difficulties that science learners have in using and understanding scientific models (see later).

One feature from the literature is an identification of the difference in status attributed to a model by learners and experts (i.e. scientists). Experts appreciate that models are human inventions and are thereby based on an incomplete understanding of how nature works. Experts use models in a very pragmatic fashion, seeing them as tools they use to help understand the world. These experts use models to concentrate attention on specific aspects in order to explain something that is not familiar in terms of something that is familiar. Consequently, most models are 'wrong' or 'limited' in some key aspect and the pragmatic use of models that are known to possess limitations is one of the characteristics that differentiates the expert from the novice (Grosslight et al. 1991).

This pragmatism that develops with increasing experience has been identified in a cross-age inquiry of learners' mental models for chemical bonding in Australia and

New Zealand (Coll 1999). This pragmatism was expressed with the learners' preference for simple or realistic mental models of chemical bonding across three academic levels (year 13, undergraduate and postgraduate). This was applied equally to models for metallic substances (Coll and Treagust 2003b), ionic substances (Coll and Treagust 2003a) or covalently-bonded substances (Coll and Treagust 2002a). Although a level of expertise was evident — senior-level learners were able to describe their mental models of chemical bonding in greater detail than their younger counterparts and were more critical of expressed or teaching mental models (Coll 1999) — many still possessed alternative conceptions (Coll and Taylor 2001).

Different views on the nature of mental models between students and those held by teachers, scientists and other experts have been documented (Ogborn and Martins 1996). Factors that may impede pupils' effective use of models and be indicators of their level of expertise are as follows:

- some learners may learn the model rather than the concept that it is meant to illustrate (Thiele and Treagust 1991, Treagust 1993);
- pupils may lack awareness of the boundary between the model and the reality the model is representing (Dyche et al. 1993, France 2000);
- unshared attributes are often a cause of misunderstanding for learners (Thiele and Treagust 1991, Thagard 1992);
- when given a range of models, some pupils continue to use the least sophisticated one (Gilbert and Osborne 1980);
- some pupils lack the necessary visual imagery (Treagust 1993);
- some pupils find it difficult to apply the model in different contexts (Gilbert and Osborne 1980); and
- pupils may mix their models; for example, they may have the concept that heat makes molecules expand (Gilbert and Osborne 1980).

Some researchers (for example, Harrison and Treagust 1996, Raghavan and Glaser 1995) argue that confusion about model use may have its origins in the mode of instruction. Smit and Finegold (1995) found that Southern African biological science teacher trainees thought of models as essentially scale models of reality — as a result of their exposure to medical models such as models of the human body, insects, skeletons, and so forth. In another professional development situation when New Zealand teachers used red dye (as a substitute for a bacteria culture) as a model for assessing an aseptic technique, their students quoted the red colour as evidence of bacteria. In this situation the teachers had not made a strong enough distinction between the model and reality (Farmer 1994). Similarly, Barnea et al. (1995) report that Israeli preservice and inservice chemistry teachers failed to distinguish between a mental image and a physical model, believing instead that a model is simply a way to describe a process or phenomenon.

In summary, the research evidence sees teachers as an important link for learners developing a more complex understanding and use of analogies and models.

## Research on teachers' use of analogies and models in classrooms

If one presumes that the use of analogy provides a link into model building and model use, then an awareness of the research on the use of analogy in curriculum materials is relevant to the argument. The literature provides evidence that the

degree of interaction between the learner and the presenter of the analogy (either by commentary or explanation in the text) determines the efficacy of learning through this media (Dagher 1995b). The use of analogies is widespread in science teaching; however, it appears that its use is frequently idiosyncratic (Thiele and Treagust 1994) and generated spontaneously when students are struggling to understand concepts (Dagher 1995a, Jarman 1996). Dagher (1995a) has identified analogy use in a variety of source domains such as actual life experience (actual and observed), science fiction, personalized stories and common objects.

It appears that use of analogies is widespread in science education, and there is research evidence demonstrating that even young students can use metaphors (Christidou et al. 1997) and that the direct comparison of mental models and analogies can aid understanding (Newton and Newton 1995).

We argue that the ability to compare and, in the long term, critique analogies and models is a behavioural indicator of expert model use. Research that identifies and evaluates strategies that reflect scientists' use of models is recorded in the literature (Dagher 1994, Lehrer and Schauble 1997, Ogborn and Martins 1996, Penner et al. 1991, Treagust 1993). Aspects of scientists' use of models that are developed to explain data, model processes and behaviour, provide predictions, and so forth (Franco et al. 1999, Greca and Moreira 2000, Harrison and Treagust 1996), have been transformed into a variety of pedagogical approaches that have been evaluated in the research literature. For example, it has been suggested that teachers should encourage students to generate their own analogies (Pittman 1999) and to critique their mental models to see where they break down with respect to scientists' mental models (Duit 1991, Venville et al. 1994).

Some examples of research that has started to unpick the efficacy of transferring an expert's (scientist) use of models into the classroom suggest that:

- enabling students to construct and critique their own models effectively supports conceptual development outcomes (Abell and Roth 1995);
- providing the opportunity to link conceptual and metacognition when working with physical models can promote positive attitudes and increased cognitive understandings (Penner et al. 1997); and
- model-based teaching approaches may develop a more pragmatic view of models where students are able to recognize the uses and limitations of the models and the modelling process (Taylor et al. 2003).

The following discussion will identify specific strategies that may contribute to this translocation.

Abell and Roth (1995) found that fifth-grade American students misunderstood a pyramid model of trophic levels in a terrarium community as representing the space needs of the organisms rather than energy relationships. However, when teachers abandoned the scientific model and allowed students to construct their own, it became evident that students did have reasonable ideas about number relationships in the terrarium community and there was evidence that this latter model had a scientific basis.

The power of linking physical activity with conceptual and metacognition was apparent from the research carried out by Penner et al. (1997), who gave American grade 1 and grade 2 learners the task of building a model that worked like a human elbow. Through discussion, model building, evaluation and revision, learners came to understand that not only motion, but also constraints on motion, were important

qualities to include in their elbow models. After the model-based teaching, samples of learners from the class were interviewed and asked to rate the functional quality of four elbow models: a picture of an arm with an arrow pointed at the elbow, a model made of two popsicle sticks joined by a lump of clay, a flexible straw, and a simple cardboard-and-string pulley model. The learners' explanations for why each model was a good model for how the elbow works were examined and compared against non-modelling grade 2 and grade 4–5 classes. In comparison with a non-modelling peer group, modellers were largely able to ignore perceptual qualities when asked to judge the functional qualities of models and showed an understanding of the modelling process similar to that of learners 3–4 years older.

Another programme provided opportunity for New Zealand students of astronomy (Taylor 2000) to critique a model in terms of its positive, negative and neutral attributes. A pragmatic view of model use was developed when these students were able to explore not only their mental astronomical models, but also the scientist's constructs. This reflection and analysis helped them understand the intelligibility and plausibility of the scientist's mental model. When this group of year 7 and year 8 New Zealand students were asked to utilize scientists' mental models to solve some novel problems, the focus of their model critique shifted from intelligibility and plausibility to fruitfulness. This pragmatism extended to an appreciation of the communication among the group for it is important to note that they found cooperative problem-solving and reporting interesting, challenging and informative.

France (1997, 2000) identified that not only was it important for teachers to have sound pedagogical content knowledge to use and develop appropriate models, but it is important that these teachers are conversant with their use within the community of experts that use them (in this case, the community of biotechnologists).

The premise that the development of an appreciation of an expert's (scientist) use of models may enhance the learning potential of science students is founded on a need to identify and characterize learners' mental models. It has also been suggested that investigating learners' mental models can provide science education researchers and teachers with valuable information about the learners' conceptual framework; that is, their underlying knowledge structures (Vosniadou 1994). However, discovering what a person's mental model is like is not easily accomplished, and learners may behave quite inconsistently in their use of mental models (Glynn and Duit 1995, Greca and Moreira 2000, Harrison and Treagust 1996, Hesse 1966).

Notwithstanding this complexity, it does seem that teachers need a broad understanding of the types of mental models that children might hold and the ways in which these are likely to differ from scientists' mental models, thereby impacting on what is actually learnt. Such understandings could well be used as part of a process for strengthening teachers' pedagogical content knowledge. There are clear implications here for policy development, and these are highlighted in the contribution by Jones and Baker in the present special issue.

In summary, the research literature indicates that helping students to understand key mental models of science as part of their conceptual development will be most effective when:

- learners are helped to understand the role that mental models play in the construction of scientific models; and to be aware of the strengths and limitations of models in describing and explaining scientific concepts;

- learners are able to construct and critique both their own models and scientists' models of scientific phenomena; and
- teachers have a good pedagogical content knowledge about the nature of science — in particular, the role of models, metaphor and analogy in scientific communities of practice — and they are also aware of the range of possible mental models of scientific phenomena that their students may hold.

However, the use of models is not only limited to students' scientific conceptual development. Gilbert et al. (2000) argue that students need to learn about how expressed models are debated and tested until a consensus decision about their status is reached within the community of scientists. This is an aspect of the sociology of science as described by Ryder (2001), and outlined by Jones and Baker in the present special issue, and shows the social justification of model use and how this needs to be factored into teaching and learning. This is now discussed.



## Sociocultural approaches to teaching and learning science for conceptual development

Model-based teaching and learning strategies provide opportunities for science education research to move away from the narrow focus of conceptual change to an examination of the wider social aspects involved in learning science (Duit and Treagust 1998). This viewpoint signals that learning about science may be as important as the development of conceptual and procedural knowledge development. This change in focus has been signalled by Duschl and Hamilton in the following:

> The fundamental question for understanding the rationality and objectivity of conceptual change involves what the basic unit of analysis is. Do we focus on individuals or communities of practice? Is the focus on the development of procedures of reasoning or on a conceptual understanding of scientific knowledge? (1998: 1061)

Thus the development of pedagogical practice that provides an opportunity for learners to identify with and emulate the type of discussion that occurs within the community of practice of scientists is of increasing importance in international science education research, and can provide significant links between the community of practice of scientists and the classroom. As Duschl and Hamilton suggest:

> Shifting the focus from knowing and reasoning by individual scientists or learners of science, to communities of scientists or learners of science, requires fundamental changes of both our images of science learning environments and of what we want students and teachers to do in those environments. (1998: 1054)

With the change in focus towards social constructivist and sociocultural research on learning there is a suggestion that the cognitive activities of individuals can be understood by examining the social and cultural contexts from which they are derived. Sociocultural views of learning endorse the view that knowledge is socially constructed and context dependent, and that human mental processes are situated within their historical, cultural and institutional setting (Wertsch 1991). This view of learning is related to the idea of situated cognition (Hennessey 1993), meaning that cognitive processes differ according to the domain of thinking and the specifics of the task context (Brown et al. 1989, Rogoff 1990). From a sociocultural perspective, learning means changing from one sociocultural context to another as a process of enculturation by participation in shared activities (Lave and Wenger 1991).

Typically, such sociocultural views of science learning promote the *community* aspect of the classroom and the role of peer discussion in assisting students to learn science. With this viewpoint, a discussion with peers has the potential to provide students with alternative models of scientific phenomena and to introduce criteria as well as evidence to help learners to distinguish among scientific models. Such an activity is enhanced with the utilization of cooperative learning strategies. Classroom-based research into cooperative learning as a means to achieve these aims in science education extends back at least to the 1970s. Many earlier studies sought to investigate the efficiency of this pedagogy in classrooms, for example, by using standardized achievement test scores or students' affective gains as indicators.

The general conclusion of research into cooperative learning is that such learning can positively enhance achievement and attitudes towards science (Lazarowitz and Hertz-Lazarowitz 1998, Lowe and Fisher 2001, Lumpe 1995). However, recent literature shows that research has moved towards a deeper examination of group work in science along several interrelated dimensions. We argue that a continuing emphasis on this research will provide evidence on how models can provide opportunities for students to learn *about* science as they take part in outcomes related to understanding the nature of science at the same time as they are developing content learning outcomes as specified in *Science in the New Zealand Curriculum* (Ministry of Education 1993).

Cooperative learning research has moved along several interrelated dimensions, but within the limitations of this paper we will examine the following issues that may be applicable to our promotion of a model-based pedagogical model that enhances sociocultural learning theories while acknowledging the embeddedness of group work in sociocultural and social constructivist theories of learning.



## Strategies that enhance a sociocultural-based pedagogy

### *Emulating scientific discourse communities; structuring productive student discussions*

Much research on group work embodies the notion that students' knowledge-building in science classrooms should have some relationship to the way that science knowledge is developed in the scientific community. In recent years, thinking about what it means to be 'doing science like a real scientist' has shifted from a focus on the individual to a focus on social context and the nature of interactions between scientists (or learners)[1] as the vehicle for knowledge change (Duschl and Hamilton 1998).

Inquiry/discovery approaches, which had been popular since the 1960s, promoted the idea that students 'doing science like real scientists' would be focused on academic, essentially cognitive, outcomes using a combination of rational thinking and discovery events. However, it has been widely suggested that discovery learning approaches neglected social, cultural and affective dimensions of science and were only partially suited to the complex and diverse context of school classrooms where these dimensions play an important role (Lazarowitz and Hertz-Lazarowitz 1998). Such complexities are evident in the research that is now reported.

- The role and use of group work in facilitating deep learning and collaborative knowledge-building in science (Hogan 1999b, Newton et al. 1999, Woodruff and Meyer 1997).

- The relationship between group work and the use of argument and discussion in science classrooms (Newton et al. 1999, Osborne et al. 2001, Sprod 1998).

*The role of group work in facilitating deep learning and cooperative knowledge building*

Woodruff and Meyer (1997) propose a model for the construction of science knowledge in classrooms that emulates the way science knowledge is developed in scientific communities. They suggest that scientists work in two types of communities using two different types of discourse. Within the scientist's laboratory, scientists discuss ideas that are not fully worked out, among peers, without high risk to their ego or career. Scientists also participate in a wider, inter-laboratory community. This more public forum sets and applies standards and benchmarks to claims of scientific knowledge and supports the arbitration that lets the discipline advance.

Woodruff and Meyer contend that classroom conditions can support these two forms of discourse when students build knowledge using a combination of small-group and whole-class work. Small-group discourse supports students as they generate explanations and build on each other's ideas, while large-group discourse places a high demand for clarity and explanatory power on the working products of the groups, and challenges the acceptability of the ideas students generate. Such deliberation could be used to develop students' learning about the nature of science outcomes if students were made aware of the differing purposes of these two types of discourse in a real community of scientists.

Woodruff and Meyer implemented this approach in grade 5 and grade 7 Canadian classes using topics such as shadows and images and floating and sinking. Their study provides qualitative evidence to suggest that it effectively promoted students' ability to develop shared, coherent understandings of these phenomena. Taylor's (2000) New Zealand-based research with solar system models, mentioned previously in this paper, also followed the pattern of alternating small-group and whole-class discussion at some stages. However, Taylor attributed the success of his intervention to the systematic critique of models. Clearly within the complexity of real classroom settings it is difficult to make conclusive judgements about the effectiveness of individual components such as 'discussion' *per se*.

Science knowledge building from group work was analysed for the depth of cognitive processing by Hogan (1999a, 1999b). He analysed the levels of cognitive processing that occurred among five groups of eighth-grade American students, working in triads, as they collaboratively built science knowledge during a 3-month investigative unit on building conceptual models of matter. The students' sense-making discussions during the unit were analysed for depth. Hogan found that two groups tended to process information on a surface level, while the other three tended to engage in deeper processing.

Interestingly, the relationship between depth of processing and scientific 'correctness' of students' ideas was not straightforward. Some groups engaged in deep processing yet expressed misconceptions about the nature of matter, albeit with high internal consistency. Other groups generated accurate explanations that were readily accepted by all members of the group but then subsequently engaged in more surface-level processing. Again, these findings suggest that

teachers need to have very clear conceptual goals in mind and that the design of the task will be critical to the successful realization of these goals as focused conceptual development.

Given findings such as these, the question arises whether, from a teaching perspective, it is more important for students to reach the 'correct' answers or for students to engage in deeper discussion and cognitive processing at the expense of 'getting it right' right away (Osborne et al. 2001).

The consensus view in the literature on group work in science from a sociocultural or social constructivist learning perspective appears to suggest that sometimes it is necessary to ease up on expecting students to construct understandings that are scientifically accurate. In this view it is important, at least initially, to allow them to experience what it is like to build original models, theories and explanations in the way that scientists do (Hogan 1999b).



### *Relationship between group work and the use of argument and discussion in classrooms*

The role of argument in science education has become a much-debated topic in recent research literature, further supporting the sociocultural view that structured discussion, and the conditions that facilitate it, are a central dimension of both science and science education (Newton et al. 1999, Solomon 1998).

A distinguishing feature of argumentation is that students are expected to draw on *evidence* for their assertions (Osborne et al. 2001), and this expectation necessitates that the materials that students work with are structured in ways that make the evidence for science theories apparent. In this manner students could well be developing understandings about how science theories are justified and validated against empirical data, as well as strengthening their understanding of the actual science concepts (Ratcliffe et al. 2001).

Not all historical models for scientific argument are appropriate for the science classroom. Solomon (1998) cautions against the 'strictly logical' style of argument favoured by Aristotle and other scientists of the enlightenment, which can be confrontational and destructive. She favours a more 'humanistic' kind of argument in which all students feel comfortable to listen to the ideas of others, to question these without angry rebuttal and to introduce their own ideas, modifications and opinions in order to build towards shared understanding. Explicit reference to evidence to support such arguments is intended to ensure that such discussions are focused towards clear conceptual outcomes.

Concept cartoons appear to be a promising way of encouraging argumentation and learning in science classrooms (Naylor et al. 2001). These simple cartoons show characters expressing different viewpoints about the science involved in an everyday situation. For example, one cartoon shows three people expressing different views about whether putting a coat on a snowman will either melt him or stop the snowman from melting, or make no difference.

Because concept cartoons present alternative ideas as a means of challenging and developing learners' thinking, they avoid the expectation that all groups of students will be able to draw a range of salient ideas from their joint personal experiences in any particular context. This helps avoid the problem of debate going in directions that are not helpful to the teacher's conceptual purpose. The provision of various pieces of *evidence* (that could be claimed to support one or more of the

cartoon views) can further sharpen both the conceptual and the metacognitive focus for the group's argumentation processes.

Current research on concept cartoons aims to explore in greater detail the nature of discussion and argumentation in primary science classes using the cartoons as a stimulus. Initial findings from pupils aged 7–9 years in the UK show that discussion is focused, purposeful and self-sustaining, and results in high levels of pupil involvement, sometimes from pupils otherwise reluctant to express their personal views (Keogh and Naylor 1999, Naylor et al. 2001).

### *The teachers' role in facilitating discussion and knowledge-building*

In summary, the consensus view in the literature on group work in science from a sociocultural or social constructivist learning theory perspective appears to suggest that sometimes it is necessary to be less concerned about student understandings that are not that scientifically accurate. In this view it is important, at least initially, to allow them to experience what it is like to build original models, theories and explanations in the way that scientists do (Hogan 1999b).

It is apparent that this change to pedagogy will require teachers to look at their roles differently, as is evident from the following research.

Newton et al. (1999) investigated the extent to which teachers provided opportunities for pupils in years 7–11 to contribute to the co-construction of knowledge through discussion and argumentation in seven London schools. They found classroom discourse to be largely teacher-dominated, and opportunities for the social construction of knowledge or the use of argument-based pedagogical techniques, were few. Discussions with teachers suggested two major barriers:

1. There were limitations in teachers' pedagogical repertoires: they felt they did not know how to manage group discussion effectively.
2. External pressures such as lack of time, demands to 'cover' curriculum and the demands of the assessment system were seen to mitigate against using such pedagogy.

Ritchie and Tobin (2001) provide further evidence of the crucial role of the teacher. During in-depth investigation of group discussions in an eighth-grade middle-school science class, Ritchie and Tobin found that students' discussions were dominated by statements that reproduced information from the textbook or teacher. These students rarely engaged in truly dialogic discussion — that is, building on the ideas generated during discussions between themselves and questioning or challenging their ideas or the information coming from the textbook or the teacher.

The teacher in Ritchie and Tobin's (2001) study used and saw the value of group work activities. However, they reported that the teacher's referent for learning science was one of exposure — that learning required students to be exposed to science for themselves (i.e. through investigative work) in order to understand — a position more akin to discovery learning. During both group and whole-class dialogue, the teacher rewarded reproductive talk and cued students towards the correct predictions. Consequently, the teacher's authority as dispenser of scientific facts was never challenged. Ritchie and Tobin suggest this was a barrier to the development of dialogic discussion in the class:

> Students need to be shown how to represent their knowledge in the form of evidence-based arguments. When students are able to challenge each other's arguments from an empirical

> position as well as one based on the authority of textbook propositions, small group discussions will move towards the discourse characteristic of a scientific discourse community. (Ritchie and Tobin 2001: 297)

While there is evidence that the teaching approaches described in this section can result in various combinations of conceptual, attitudinal and nature of science learning outcomes, there are tensions in the research reported in this section between what researchers may see as ideal and what teachers are prepared or are able to do in practice. Clear thinking about the intended content knowledge, attitudinal and nature of science learning outcomes would appear to be a necessary first step to designing learning tasks to promote argumentation as an approach to structured discussion.

*Can group work enhance model-based learning?* Classroom research indicates that pedagogies involving whole-class and/or small-group discussion activities can promote conceptual learning, metacognitive learning, nature-of-science learning and/or positive student attitudes in science classrooms. For example:

- Pedagogy that encourages students to develop their discussion skills through structured argumentation has been a focus of a range of recent research projects.
- Students may achieve different types of outcomes through argumentation, depending on the design of the task and their degree of engagement with it.
- Skillful task design and teacher clarity about intended outcomes impact directly on the outcomes actually achieved.
- Content learning outcomes are achieved when students think deeply about the manner in which evidence does or does not support their personal theories about science concepts.
- Nature of science learning outcomes are achieved when students recognize that science theories are similarly tested against evidence that has been systematically collected from the natural world.



## Conclusions and suggested areas of research

The classroom research literature reviewed in this paper provides a number of clear implications for pedagogy aimed towards raising student achievement in science. Evidence for raised achievement has surfaced in studies across this paper both in terms of improving content knowledge learning outcomes and in terms of promoting other positive learning outcomes related to students' attitude, motivation and understandings about the nature of science.

A common theme to emerge in studies reported in this paper is that, in order to successfully develop conceptual understandings in science, learners need to be able to reflect on and discuss their understandings of scientific concepts as they are developing them. A significant body of research relating to the role of mental models, physical models, metaphors and analogies in science teaching indicates that pedagogies involving various types of modelling are most effective when students are able to construct and critique both their own, and scientists' models of scientific phenomena. The effectiveness of these pedagogies has been measured in terms of both conceptual learning and understanding the nature of science learning outcomes. That is, students in some studies appear to have learned not only the

content of a particular science concept, but also uses and limitations of models as a representational tool.

Research also indicates that group work and peer discussion can be vital components of successful teaching to enhance students' cognitive *and* metacognitive thinking skills. In the studies reviewed here the development of social interaction through group work and discussion was typically not seen as an end in itself, but was a medium for promoting students' deep conceptual development in science.

As yet there are no New Zealand classroom studies that monitor the impact of group work using a model-based pedagogy. Such research would provide opportunities for students to develop self-awareness of their thinking processes when using models and provide strategies for teachers to develop the learning outcomes relating to the nature of science that *Science in the New Zealand Science Curriculum* (Ministry of Education 1993) specifies. Further research may provide the evidence that the explicit metacognitive use of models and analogies may be an appropriate choice of pedagogy to integrate the development of science concepts while developing students' understanding of the 'Nature of Science'.



## Note

1. An important difference is that outcomes for scientists include *adding to* the existing stock of knowledge, whereas outcomes for students focus on conceptual development – that is coming to a more coherent *understanding* of concepts from the existing stock of knowledge.

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